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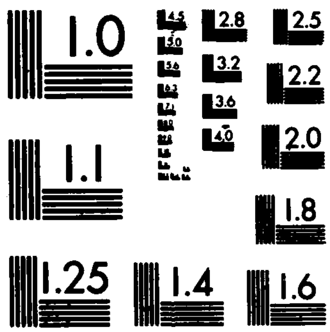
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RIMAIR VS. CURRENT ASO POLICY:
A COMPARATIVE ANALYSIS OF TWO METHODS
FOR DETERMINING AVCAL STOCKAGE LEVELS

by

Brooks O. Boatwright, Jr.

September 1983

Thesis Advisor: F.R. Richards

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RIMAIR vs. Current ASO Policy: A Comparative Analysis of Two Methods for Determining AVCAL Stockage Levels

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TABLE OF SYMBOLS AND ABBREVIATIONS

AA - Attrition Allowance

ASO - Naval Aviation Supply Office

AVCAL - Aviation Consolidated Allowance List

BCM - Beyond the Capability of Local Maintenance

BP - Basic Pipeline

CNO - Chief of Naval Operations

CT - Cost Target

CV - Coefficient of Variation

END - Endurance Level

ESS - Essentiality

FMSO - Fleet Material Support Office

FR - Fill Rate

MRP - Mean Repair Pipeline

MRSP - Mean Resupply Pipeline

MTBF - Mean Time Between Failures

MTTR - Mean Time to Restore

OLP - Operating Level, Peacetime

OSTP - Order and Shipping Time, Peacetime

OSTW - Order and Shipping Time, Wartime

QAP - Quarterly Attrition, Peacetime

QAW - Quarterly Attrition, Wartime

QRW - Quarterly Removals, Wartime

RIMAIR - Retail Inventory Model, Aviation

RPA - Rotatable Pool Allowance

S - Stockage Level

SRT - Supply Response Time

TAT - Turnaround Time

UP - Unit Price

WP - Wartime Pipeline

I. INTRODUCTION

A. BACKGROUND

One of the key ingredients of an effective weapon system is ensuring that the system is in a working condition when needed. As Naval aircraft become increasingly complex with multitudes of electronic components, the problem of keeping them flying and capable of performing all their assigned missions becomes more difficult. Since it is unlikely that a totally reliable system (one that never breaks down) can be designed in the near future, the question of how to restore such systems to operating condition is inevitable.

The concept of "remove and replace" is utilized by the Navy in an effort to minimize the non-availability of its aircraft when breakdowns occur [Ref. 1]. Under this policy a malfunctioning item is removed and immediately replaced by an operable one. This leads to a requirement for spare items at the retail (operating) level. It is the purpose of this thesis to compare two methods of determining which spare items and how many of them should be stocked at the retail level for Naval aircraft. In this chapter the problem, and the data base are discussed.

Quantities of aviation material to be stocked at the retail level are managed by the Naval Aviation Supply

Office (ASO) [Ref. 1] with policy prescribed by OPNAVINST. 4441.21 [Ref. 2]. AVCAL's (Aviation Consolidated Allowance Lists) are used to delineate actual stockage levels. ASO has used the same basic rules for determining AVCAL's since the late 1960's [Ref. 3]. However, the Fleet Material Support Office (FMSO) [Ref. 4] verified that the stockage levels prescribed by these rules are inadequate to meet the goals of the Chief of Naval Operations (CNO) to satisfy 75% of all demands and 85% of demands for stocked items. As a result, the Fleet Material Support Office has developed an alternative model called the Retail Inventory Model, Aviation (RIMAIR). In Chapter II, the theoretical and functional aspects of both RIMAIR and the current stockage rules are explained.

Since each model operates under different rules and assumptions it is likely that they will yield different AVCAL's. The TIGER simulation model, discussed in Chapter III, is utilized to compare the two stockage models based on the availability of three hypothetical systems.

Finally, Chapter IV covers a comparison of forecast stockage levels, and the results of the TIGER simulation.

B. THE DATA

The data utilized for this study were obtained from the ASO master data file. As such, the data are the same as that used currently to determine AVCAL stockage levels.

The data consists of slightly over forty-three thousand parts from the T-56 jet engine.

For each part the following data are provided:

1. Naval Inventory Identification Number (NIIN)--a nine digit identifier.
2. Unit Price (UP)--the cost of an individual item.
3. Consumable/Repairable Code (CR)--identifies the part as either a consumable (C) or repairable (R). This is critical since different stocking policies are currently applied to each. Since this study deals with retail stockage levels, all parts requiring depot level repair are classified as consumables.
4. Order and Shipping Time, War (OSTW)--the expected length of time required to order and receive a part under wartime conditions when one is not available at the operating level. OSTP is the equivalent length of time under peacetime conditions. The RIMAIR model assumes OSTP = OSTW.
5. Quarterly Removals, War (QRW)--the total quantity of an item that are removed and thus require replacement (i.e., demands) during a 90-day period assuming wartime flying hours.
6. Quarterly Attrition, War (QAW)--the quantity of an item that are discarded from the resupply/repair pipeline (see Figure 1) during a 90-day period under wartime conditions. For consumables, QRW = QAW

(all consumables that fail are discarded), and for repairables QRW $\geq$ QAW. The difference between QRW and QAW is the quantity of an item that are successfully repaired during the quarter.

7. Quarterly Attrition, Peace (QAP)--similar to QAW but assuming peacetime flying hours.
8. Mean Repair Pipeline (MRP)--the expected number of an item that are in the repair pipeline at any given time under steady-state conditions.

II. RETAIL INVENTORY MODELS

A. THE CURRENT ASO RULES

ASO's current procedure for determining AVCAL stockage levels is based on the repair/resupply pipeline model in Figure 1. Demands (QRW) are placed on the supply system due to actual failures or the removal of items for preventive maintenance. Upon entering the system, a part is determined, with probability p, to be beyond the capabilities of local maintenance (BCM), or with probability 1-p it is determined to be repairable.

If the item is classified as BCM it is discarded (QA) from the retail level (it may be repairable at a higher level) and a replacement part is ordered. Ordering an item from outside the operating level will entail a delay due to order and shipping time (OSTW). OSTW is assumed constant for a given item by the RIMAIR model.

If repairable, an item is placed in the repair pipeline. The average time spent being repaired is the turnaround time (TAT) and the average number of an item in the repair pipeline at a given time is its mean repair pipeline (MRP). When repairs are complete the item is returned to the retail level inventory.

The following assumptions are made concerning the repair/resupply model [Ref. 4]:

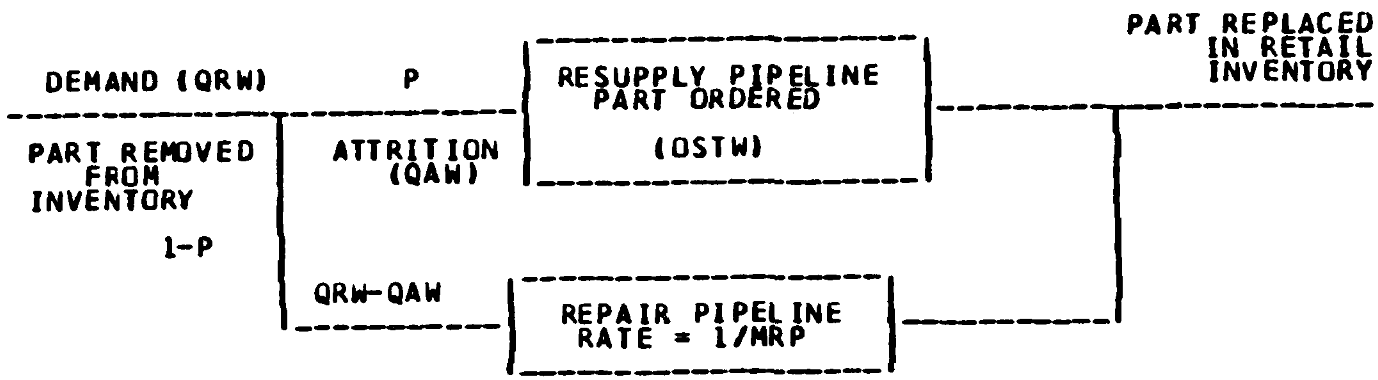


FIGURE 1. RETAIL INVENTORY MODEL

1. Demand is a Poisson process.
2. Demand rates are stationary over time.
3. OSTW and TAT are independent of demand.
4. Items are requisitioned on a one-for-one basis (S-1,S ordering policy).
5. All demands are satisfied by either immediate replacement from supply, expeditious repair, or requisitioned (back ordered).
6. There is no cannibalization.
7. The repair pipeline is never saturated (there are always sufficient repairmen to work on all items entering the repair pipeline).

As a direct consequence of assumption one, demand over a given time period (measured in quarters) is Poisson distributed with mean of $QRW \times t$. Based on the assumptions, Ross [Ref. 5] showed that the repair pipeline and resupply pipeline are themselves independent Poisson processes with rate parameters $(1-p) \times QRW$ and $p \times QRW = QAW$ respectively. Ross then showed that the number of items being repaired, the number of items requisitioned and the total number of items in the system at a given time are each Poisson distributed with means of MRP, mean resupply pipeline (MRSP) and MRP + MRSP.

Based on the resupply/repair pipeline model and the fact that the number of items being repaired are Poisson distributed, ASO devised the stockage rules outlined in

Table 1. They provide for separate range (will the item be stocked?) and depth (given it is stocked, how many will be stocked?) criteria based on unit cost and demand. The

TABLE 1

CURRENT ASO RANGE AND DEPTH CRITERIA

ALLOWANCE QUANTITY	RANGE CRITERIA	DEPTH CRITERIA
Rotatable Pool (RP)	Repair demand during IMA TAT (intermediate maintenance activity turn around time) $\geq .11$	90% protection on repair demand during IMA TAT
Attrition with RP	Quarterly attrition demand ≥ 1.0	Quarterly attrition demand rounded at .5 with a minimum of one
Attrition without RP	Quarterly attrition demand $\geq .34$ if unit price < $5000 -------------------- Quarterly attrition demand $\geq .5$ if unit price $\geq$ $5000	Same as attrition with RP

rotatable pool allowance (RPA) provides 90% protection for those parts tied up in the repair pipeline. In other words,

$$P(X \leq RPA) = .9 \qquad \text{(II.A.1)}$$

where:

X = the number of items being repaired.

And since X is Poisson distributed,

$$P(X \leq RPA) = \sum_{X=0}^{RPA} e^{-MRP} \frac{(MRP)^X}{X!} \qquad \text{(II.A.2)}$$

If MRP $\geq$ .11, then an RPA is allowed. An MRP = .11 is the minimum MRA that will require an RPA of one.

The attrition allowance (AA) is designed to account for losses due to non-repairable (BCM) parts. Range criteria for the AA differ depending on whether an RPA is allowed. In the case of repairables with MRP $\geq$ .11 (RPA allowed), the range criterion is a quarterly attrition demand (QAW) $\geq$ 1.0. For consumables and those repairables with an MRP < .11, the range rules differ based on unit price (UP) and QAW. If UP < 5000, a QAW $\geq$ .34 is required for an attrition allowance (AA) and if UP $\geq$ 5000, a QAW $\geq$ .5 is needed. In either case, attrition allowance with RPA or attrition allowance without RPA, the depth criteria are the same. Given that one of the range criteria is met, an AA equal to the QAW (rounded to the nearest non-zero integer) is allowed.

Once the rotatable pool allowance and the attrition allowance have been computed, they are added to yield the AVCAL stockage level.

B. RIMAIR MODEL

RIMAIR (Retail Inventory Model, Aviation) is advertised as an essentiality weighted (see Section II.B.5), fill rate optimization model with a cost constraint. It is based on the resupply/repair pipeline model discussed in the previous section (see Figure 1). The same assumptions hold.

1. The Lagrangian

RIMAIR uses basic Lagrange multiplier techniques for optimization. In standard format, RIMAIR solves the following problem:

$$\text{Maximize} \sum_{\text{ITEMS}} ESS(i) \times QRW(i) \times FR$$

$$\text{Such that} \sum_{\text{ITEMS}} UP(i) \times S(i) \leq CT \tag{II.B.1}$$

where:

ESS(i)	=	essentiality code for item i;
QRW(i)	=	quarterly demand for item i;
UP(i)	=	unit price for item i;
S(i)	=	stockage level (depth) of item i;
CT	=	cost target (budget); and
FR	=	the probability of satisfying a demand for item i at time t (fill-rate).

The above definition of fill-rate is used by the RIMAIR model but is not universally accepted. Operational personnel measure a quantity they call fill-rate as the ratio of total number of demands filled to the total number of demands. The latter definition is called stockage level effectiveness in this study. The two are not the same. Appendix B discusses both definitions in more detail.

Based on the above maximization problem the Lagrangian is:

$$L(\overline{S},\lambda) = \sum_{ITEMS} [ESS(i) \times QRW(i) \times \sum_{X=0}^{S(i)-1} p(x)]$$

$$- \lambda [\sum_{ITEMS} (UP(i) \times S(i)) - CT] \qquad (II.B.2)$$

where:

$\sum_{X=0}^{S(i)-1} p(x)$ = fill-rate (FR) (see Section II.B.2).

Although Equation II.B.2 is a discrete function the RIMAIR model treats it as though it were continuous. Thus, upon differentiation with respect to S(i) and setting the result equal to zero, the optimal stockage level is:

$$p(S(i)-1) = \frac{\lambda \; UP(i)}{ESS(i) \; QRW(i)} \qquad (II.B.3)$$

where:

p(S(i)-1) = the probability of having S(i)-1 units in the resupply/repair pipeline.

2. <u>p(x)</u>

The probability mass function, p(x), is the steady-state distribution of the total repair/resupply pipeline.

In Section II.A. it was shown that p(x) is a Poisson distribution with mean of MRP + MRSP. In terms of the data this quantity is called the mean wartime pipeline and is defined as:

$$WP = MRP + (OSTW + RDT) \times \frac{QAW}{90} \qquad \text{(II.B.4)}$$

where:

MRP	=	mean repair pipeline;
OSTW	=	order and shipping time;
RDT	=	resupply delay time (assumed equal to zero for this study); and
QAW	=	quarterly attrition.

Thus,

$$\sum_{X=0}^{S(i)-1} p(x) = \sum_{X=0}^{S(i)-1} e^{-wp} \frac{(wp)^X}{X!} \qquad \text{(II.B.5)}$$

This represents the probability that the number of units in the pipeline is strictly less than the number of spares available. Thus, at least one item will not be in the resupply/repair pipeline and will be available to satisfy demands. This probability is, by definition, the fill-rate.

3. <u>Optimization Routine</u>

RIMAIR follows the procedure below in selecting the optimal stockage level:

1. Select the Lagrange multiplier (lambda value).

2. Find p(x), where x is the largest integer $\leq$ WP.

3. If

$$p(x) < \frac{\lambda\ UP(i)}{ESS(i)\ QRW(i)}$$

then the optimal stockage level is equal to zero.

4. If

$$p(x) \geq \frac{\lambda\ UP(i)}{ESS(i)\ QRW(i)}$$

then the optimal stockage level equals the smallest integer such that

$$p(x) < \frac{\lambda\ UP(i)}{ESS(i)\ QRW(i)} .$$

5. Compare the optimal stockage level to the external constraints and adjust accordingly (see Section II.B.4).

6. Compare the total cost of the stockage levels across all items to the cost target. If the costs are not equal return to Step 1.

Note that this procedure implicitly determines the range of items to be stocked to be those items for which the depth is found to be positive. That is, if the optimal stockage level is greater than zero, then the item is stocked.

4. <u>External Constraints</u>

Step five of the optimization routine consists of a minimum and a maximum constraint that are imposed on the optimal solution.

The maximum constraint is the sum of a ninety-nine percent protection on the mean basic pipeline (BP) (.99 protection selected by RIMAIR) and the peacetime operating level (OLP). BP is defined as:

$$BP = WP + \text{ENDURANCE LEVEL} \qquad \text{(II.B.6)}$$

where WP is defined by Equation II.B.4 and

$$END = \text{Maximum} \begin{cases} (1 - \frac{RST}{90} - \frac{OSTW}{90})\,QAW + (\frac{OSTP}{90} \times QAP) \\ 0 \end{cases} \qquad \text{(II.B.7)}$$

The endurance level is the sum of peacetime attrition during the order and shipping time, plus that portion of wartime attrition not accounted for during resupply delay time and order and shipping time. The origin of the endurance level and its justification are unclear. The basic pipeline is assumed to be Poisson distributed with a mean of BP. Thus the .99 protection level would be the smallest quantity S such that:

$$\sum_{X=0}^{S} e^{-BP} \frac{(BP)^X}{X!} \geq .99 \qquad \text{(II.B.8)}$$

The peacetime operating level is merely an economic order quantity [Ref. 6] and is a function of peacetime attrition demand (QAD), holding costs (I), unit price (UP) and the cost to place an order (A). Reference [6] defines the operating level as:

$$OLP = \sqrt{\frac{2A(QAP)}{I(UP)}} \qquad \text{(II.B.9)}$$

As used in RIMAIR, the quantity 2A/I is assumed constant by the model (approximately 559).

The maximum constraint is then the sum of that quantity defined by Equation II.B.8 and OLP.

The minimum constraint (SMIN) on the optimal stocking level is:

$$SMIN = OLP + BP \qquad \text{(II.B.10)}$$

which is the sum of the peacetime operating level and the mean basic pipeline.

5. Essentiality Code

As currently used by RIMAIR, the essentiality code (ESS) equals one for all items. As a result, the essentiality of a system component is not reflected in the computed stockage levels. This shortcoming of RIMAIR is due to a lack of consensus on how to determine item essentiality and was cited by Reference 7 as a key to the more effective use of RIMAIR. It is the purpose of this section to propose an essentiality coding scheme.

Reference 8 defines item essentiality as,

> a measure of an item's military worth in terms of how its failure, if a replacement is not immediately available, would affect the ability of a weapon system, end item, or organization to perform its intended task.

Based on this definition, the following represent the desirable properties of an essentiality code:

1. An item is more essential if its failure will cause the entire system to fail. Thus, items that lack redundancy (series systems) are more essential than those with redundancy built in (parallel systems).
2. An item is more essential if its average availability is lower. Average availability is defined as:

$$\text{AVG. AVA.} = \frac{\text{EXPECTED UPTIME}}{\text{EXPECTED UPTIME + EXPECTED DOWNTIME}} \qquad \text{(II.B.11)}$$

   and reflects both the frequency of failure of an item and the time required to repair/replace the item.

Note that the definition of item essentiality refers to failures when a "replacement is not immediately available." Therefore, for the purposes of computing average availability for essentiality codes it is assumed that no replacement is in stock at the retail level. The following definitions then apply:

1. Expected uptime is the mean time between failures of an item (MTBF).
2. The expected downtime will be the sum of replacement time and order and shipping time for consumables.

For repairables it will be the sum of the replacement time (RT) and the weighted average of the turnaround time and the order and shipping time. Thus, for consumables,

$$E[\text{DOWNTIME}] = RT + OSTW \qquad \text{(II.B.12)}$$

and for repairables

$$E[\text{DOWNTIME}] = RT + \left(\frac{QAW}{QRW}\right) \times OSTW) + \left(1 - \frac{QAW}{QRW}\right)(TAT) \qquad \text{(II.B.13)}$$

Based on the above characteristics, the following essentiality coding scheme is proposed for use with the RIMAIR model. The item essentiality shall consist of two components. The first is the redundancy factor which is equal to one if the failure of an item will cause the system to fail (series), and zero if the failure of an item will not cause the system to fail (parallel). The second component is the non-availability factor and is equal to,

$$\text{NON-AVAIL.} = 1 - \text{AVG. AVAIL.} \qquad \text{(II.B.14)}$$

The two components are then added to produce the item essentiality code. Table 2 provides item essentiality values under various circumstances.

The justification for defining item essentiality in this manner is that it meets the desirable characteristics

TABLE 2

ITEM ESSENTIALITY

	AVAILABILITY					
REDUNDANCY	.99	.9	.7	.5	.3	.1
SERIES	1.01	1.1	1.3	1.5	1.7	1.9
PARALLEL	.01	.1	.3	.5	.7	.9

of essentiality and is applicable to the RIMAIR model. RIMAIR requires that stockage levels be a nondecreasing function of item essentiality. The proposed method increases essentiality whenever availability or redundancy decrease. This meets both the needs of RIMAIR and the desirable characteristics of item essentiality discussed earlier.

The proposed method does have several drawbacks. First, the method is completely arbitrary and in no way "optimal." It was designed to meet two general characteristics of item essentiality and to work with RIMAIR. Second, the range of values for item essentiality is limited under this method to the interval [0,2]. This may prove too restrictive a range to provide significant improvement. Finally, this procedure allows only two levels (0 or 1) for the redundancy factor. Thus, even though one item may have only one backup, it receives the same redundancy factor as an item with two or more backups. However, this procedure is functional and is utilized for the TIGER simulation discussed in IV.C.

III. TIGER SIMULATION MODEL

TIGER is the name of a family of programs designed to evaluate, by simulation, a complex system in terms of reliability, readiness and availability. Reference 9 is the TIGER Manual which gives a detailed explanation of TIGER's operation. The following briefly describes the capabilities and limitations of the TIGER model.

A. INPUT

Input requirements for TIGER can be broken into four main categories:

1. Simulation Control
2. Equipment Characteristics
3. Configuration and Operation Rules, and
4. Additional Output Specifications

Within these main groups the key inputs used in this study included:

1. System configuration--the actual reliability block diagram of the system is programmed.
2. MTBF--the mean time between failures for each component in the system.
3. MTTR--the mean time to restore the system to an operational status. This refers to the time required to remove and replace an item and is not the same as turnaround time.

4. Spares allocation--spares may be allocated at three levels (organizational, intermediate, and depot). In addition, the supply response time (SRT) may be designated for moving spares from one level to another.
5. Length of individual mission and number of missions simulated.

Appendix C contains sample input and output from TIGER.

B. COMPUTER SIMULATION

TIGER is a Monte Carlo simulation model that uses next-event simulation techniques. TIGER recognizes five distinct events [Ref. 9]:

1. Equipment failure (up-to-down status)
2. Equipment replacement (down-to-up status)
3. Change of operational phase within the mission (not used in this study)
4. Beginning of the mission
5. End of the mission

The last three events are input parameters and the first two are exponentially distributed random variables. Specifically, equipment failure times are drawn from a constant failure rate exponential distribution with mean equal to the MTBF of the item. In the same manner, equipment replacement times are drawn based on MTTR.

An event queue is the heart of the TIGER simulation model. Initially, failure times are generated for all components in the system (components are assumed to be up initially) and stored chronologically in the event time vector [Ref. 9]. The next event occurs at the first (earliest) time in the vector. The mission clock is advanced to this next event time and all necessary updating is performed. This includes changing the status (up or down) of the component, generating a new failure or replacement time as appropriate and placing it in the event time vector, and updating the number of spares remaining. Also, at each event time, the total system status is checked. Based on the reliability block diagram, the system is determined to be either up or down and appropriate statistics are collected. At the completion of this process the clock is advanced to the subsequent event time in the event time vector and the cycle repeats itself. This continues until the individual mission and all repetitions of that mission are complete.

C. OUTPUT

TIGER provides a total of six output options. These range in complexity from four basic measures of effectiveness to a complete event-by-event description of individual item failures and system status. In the latter case the printout is quite voluminous so caution is urged in its selection.

For this study only the management summary output option was used (see Appendix C for a sample). The management summary provides an echo of the input data followed by the four TIGER defined measures of effectiveness listed below:

1. Average Availability $= \dfrac{\text{Sum of uptime for all missions}}{\text{Total mission time}}$

2. Instantaneous Avail. $= \dfrac{\text{\# missions up at time t}}{\text{total \# of missions}}$

3. Reliability $= 1 - \dfrac{\text{\# of missions failures}}{\text{total \# of missions}}$

4. Readiness $= \dfrac{\text{Sum of uptime for all missions through the first failure}}{\text{Sum of total mission time}}$

Due to a lack of any well defined mission profiles for the data used in this study, the only measure used was average availability. The remainder of the management summary gives a breakdown of failure by individual components, a breakdown of average spare usage, and a list of critical equipments based on non-availability of the individual items. Although not utilized for this study, the last three outputs proved useful in understanding how TIGER operates.

D. ADAPTATION OF TIGER FOR THIS STUDY

TIGER required several assumptions and adjustments for use in this study. This was necessary because of the way TIGER treats repairs.

TIGER defines MTTR as the mean time to restore a failed component to an operable condition. This is accomplished by replacing the failed item with a spare from the lowest logistical level (organizational/intermediate/depot) having available spares. Thus, MTTR represents the remove and replace time for an item and not the time required to fix a repairable item (turnaround time). For the hypothetical systems simulated using TIGER no MTTR values were available. Thus, in order to prevent the MTTR parameter from driving the results, a value of MTTR = 1 hour was selected for all items. This value was chosen sufficiently smaller than the lowest MTBF so that the computation of average availability would be most sensitive to the stockage levels and MTBF vice the assumed MTTR.

TIGER provides no capability to simulate the repair pipeline. A failed item is treated as BCM and replaced with a spare from the logistic system. If a spare is available at the organizational (operating) level the replacement time is set equal to the equipment repair time (an exponentially distributed random variable with mean of MTTR). If no spares remain at the organizational level, the replacement time is equal to the equipment repair time plus a constant supply response time (assuming spares are available at either the intermediate or depot level).

The above limitation presented a problem in the case of repairables. To overcome this problem the logistics system was used as a surrogate repair pipeline. The AVCAL stockage level for each item was placed at the lowest (organizational) logistic level. An infinite number of spares were placed at the intermediate level if the AVCAL stockage level for the item was non-zero. Finally, the supply response time was set equal to the item's turnaround time. Thus, upon failure of a repairable, a replacement was drawn from the organizational level if one was available. This simulated the remove and replace process. If no spares remained at the organizational level one was taken from the intermediate level after a delay equal to the item's TAT. This simulated the case where no spares remain and an item is cycled through the repair pipeline prior to being reinstalled.

The surrogate repair pipeline treats all failures as non-BCM. This is equivalent to saying that an item has QAW = 0. Therefore, to keep the simulation as realistic as possible, only those repairables with QAW = 0 were chosen for use with TIGER.

IV. RESULTS

A. BASE CASE

The aggregate stockage level results utilizing the current ASO range and depth rules, RIMAIR with the consumable data, and RIMAIR with the repairable data are given in Tables 3, 4 and 5. Range (a maximum of 3893 for consumables and 1926 for repairables, see Appendix A) and total depth (sum across all items) figures are provided, but the key statistics are the total cost and stockage level effectiveness. Total cost is merely the sum of the individual unit prices multiplied by the stockage levels. The stockage level effectiveness is based on a 90-day endurance period with no resupply. It assumes 100 percent of the AVCAL is on board at the start of the period. Although not specifically addressed by the CNO, the above effectiveness measure is the common measure of AVCAL effectiveness [Ref. 4]. In addition, the effectiveness applies only to those items stocked (those with a positive depth) vice all items with a non-zero demand.

TABLE 3

AGGREGATE STOCKING LEVELS FOR CURRENT ASO RULES

	RANGE	TOTAL DEPTH	TOTAL COST	STOCKAGE LEVEL EFFECT.
REPAIRABLES	781	2280	4921277.00	0.8034
CONSUMABLES	2206	13478	448293.75	0.8879

TABLE 4

AGGREGATE STOCKAGE LEVELS USING RIMAIR (CONSUMABLES)

LAGRANGE MULT.	RANGE	TOTAL DEPTH	TOTAL COST	STOCKAGE LEVEL EFFECT.
1.0E-10	3398	198510	1790222.00	1.0000
1.0E-09	3398	198069	1775393.00	1.0000
1.0E-08	3398	197728	1760887.00	1.0000
1.0E-07	3398	197369	1733721.00	1.0000
1.0E-06	3398	196825	1674926.00	1.0000
1.0E-05	3393	195753	1445725.00	0.9999
1.0E-04	3343	193783	1161490.00	0.9995
1.0E-03	3294	192528	1074232.00	0.9989
1.0E-02	3293	192520	1074211.00	0.9989
1.0E-01	3293	192520	1074211.00	0.9989

TABLE 5

AGGREGATE STOCKAGE LEVELS USING RIMAIR (REPAIRABLES)

LAGRANGE MULT.	RANGE	TOTAL DEPTH	TOTAL COST	STOCKAGE LEVEL EFFECT.
1.0E-16	1466	11288	19131264.0	0.9945
1.0E-14	1466	11251	19086000.0	0.9945
1.0E-12	1466	11206	19000992.0	0.9945
1.0E-10	1466	11135	18826880.0	0.9945
1.0E-08	1466	11056	18541168.0	0.9944
1.0E-06	1462	10711	15411617.0	0.9940
1.0E-04	1289	8982	10269303.0	0.9818
1.0E-02	1047	8479	9641546.00	0.9623
1.0E+00	1044	8475	9639776.00	0.9642
1.0E+02	1044	8475	9639776.00	0.9642

The actual computation of the effectiveness figure is discussed in Appendix A.

Current ASO AVCAL stocking policy is completely deterministic. Assuming that the input values of MRP, QAW and UP are accurate, there is only one stockage level for each item. In the case of repairables this rule provided an aggregate effectiveness of .8034 at a cost of 4.92 million dollars. For consumables the effectiveness was .8879 at a total cost of .45 million dollars. The effectiveness figures are comparable to those found in Reference 4 using different data (approximately .81 and .87). The effectiveness figures also confirm that in the case of repairables the current rules are inadequate in meeting the CNO's goal of .85. This disparity is even greater when it is noted that the effectiveness calculation for repairables is an optimistic approximation of the true effectiveness (see Appendix B).

The RIMAIR model offers the capability to allow budget constraints to dictate stocking levels while still optimizing fill-rate. By selecting the appropriate Lagrange multiplier (lambda value) any budget within the bounds of the external constraints can be met. These constraints consist of a minimum and maximum stocking level for each item and are more fully explained in Section II.B.4.

RIMAIR clearly provides higher effectiveness and is able to meet the CNO's goal even at the minimum constraint.

However, it accomplishes this by stocking a greater range and depth of items resulting in substantially higher costs. Unfortunately this provides little evidence that RIMAIR is a better model than the current ASO rules and makes any comparison difficult.

Figures 2, 3, and 4 depict graphically a range of possible budgets and the resulting effectiveness that are summarized in Tables 4 and 5. They dramatically show the effect of the minimum and maximum constraints. The result of the external constraints is to desensitize the total cost and effectiveness measures to the lambda parameter. Their impact is significant for both repairables and consumables, but is particularly restrictive for the consumables. While total cost for the consumable ranges between 1.07 and 1.78 million dollars, the effectiveness is bounded between .9989 and 1.00. This indicates the high cost (about a 70% increase in the total cost) to attain the final .001 of effectiveness, but also brings into question the use of the minimum constraint in RIMAIR. It does not seem reasonable to force effectiveness levels so high with the corresponding cost increases. In essence, the flexibility of RIMAIR has been greatly reduced by the minimum constraint (Equation II.B.10).

In an effort to improve the range of costs and effectiveness available from RIMAIR and in order to compare the two models on an equal cost basis the minimum constraint

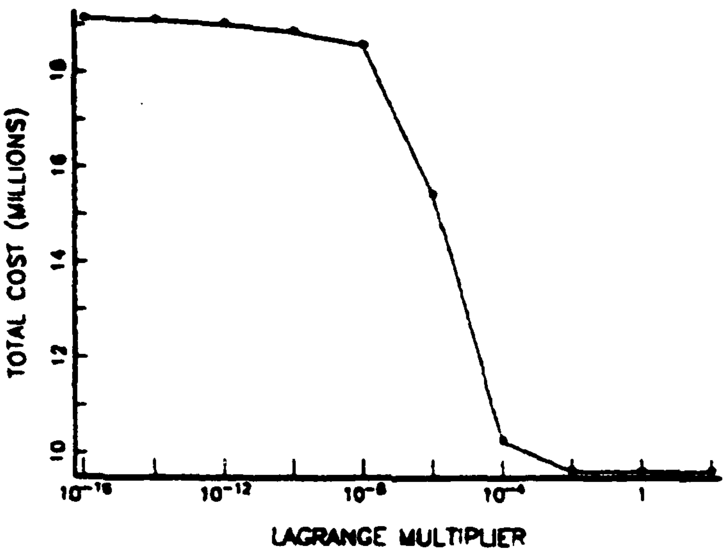


Figure 2. Total Cost Vs. Lagrange Multiplier
(Base Case, Repairables)

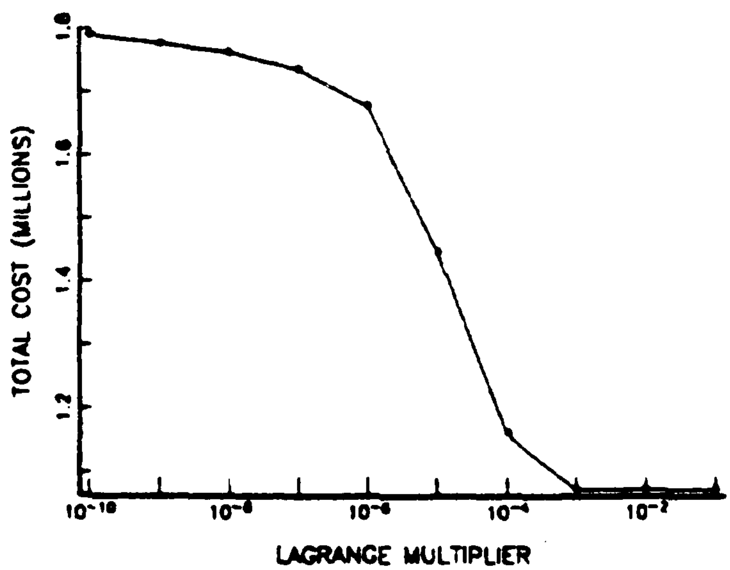


Figure 3. Total Cost Vs. Lagrange Multiplier
(Base Case, Consumables)

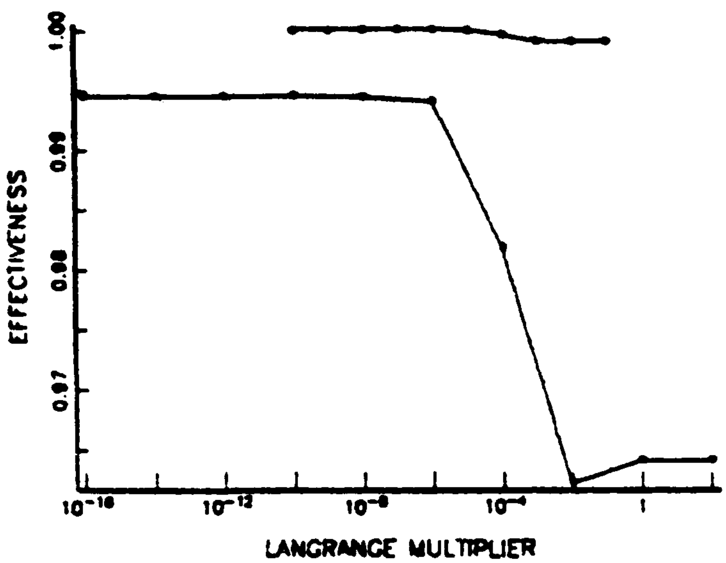


Figure 4. Effectiveness Vs. Lagrange Multiplier
(Base Case)

was removed (set equal to zero). The RIMAIR optimization routine was then permitted to function at any budget level below the maximum. The aggregate results are summarized in Tables 6 and 7 with graphical depiction in Figures 5, 6, and 7. Note that at the lower lambda values the maximum constraints dominates and the removal of the minimum constraint has little effect. However, as lambda increases the cost and effectiveness continue to decrease when the minimum constraint is removed. Given a sufficiently large lambda, the cost and effectiveness would reach zero.

The ability to compare RIMAIR and the current ASO rules on an equal cost basis now exists. For repairables, an effectiveness of .9504 was obtained at a cost of 5.08 million dollars using RIMAIR. Current ASO rules utilized approximately the same amount of money (4.92 million dollars) but attained an effectiveness of only .8034. For consumables the results were even more significant. Using a budget less than half that of the current rules (.206 million as compared to .448 million) RIMAIR attained an increase in effectiveness from .8869 to .9841. In the case of consumables this was accomplished by increasing the range and decreasing the depth of items stocked. For repairables both the range and depth increased indicating that RIMAIR must have stocked more of the lower priced items than the current ASO rules allow. Therefore, based on stockage level effectiveness, the RIMAIR model with minimum constraint removed is more cost effective.

TABLE 6

AGGREGATE STOCKAGE LEVELS USING MODIFIED RIMAIR (CONSUMABLES)

LAGRANGE MULT.	RANGE	TOTAL DEPTH	TOTAL COST	STOCKAGE LEVEL EFFECT.
1.0E-10	3390	130604	1758641.00	1.0000
1.0E-09	3390	127836	1739060.00	1.0000
1.0E-08	3390	124903	1717957.00	0.9999
1.0E-07	3390	121663	1682401.00	0.9999
1.0E-06	3390	117894	1613697.00	0.9998
1.0E-05	3385	113171	1359965.00	0.9995
1.0E-04	3327	106947	914275.44	0.9983
1.0E-03	3091	99284	485212.81	0.9944
1.0E-02	2387	89316	206086.12	0.9841
1.0E-01	1993	75990	116462.87	0.9804
1.0E+00	1276	52671	87227.37	0.9752
1.0E+01	985	22036	78822.06	0.9383

TABLE 7

AGGREGATE STOCKAGE LEVELS USING MODIFIED RIMAIR (REPAIRABLES)

LAGRANGE MULT.	RANGE	TOTAL DEPTH	TOTAL COST	STOCKAGE LEVEL EFFECT.
1.0E-16	1466	8017	19125728.00	0.9945
1.0E-14	1466	7875	19077136.00	0.9945
1.0E-12	1466	7716	18987584.00	0.9944
1.0E-10	1466	7513	18805632.00	0.9943
1.0E-08	1466	7271	18503360.00	0.9937
1.0E-06	1462	6715	15280751.00	0.9914
1.0E-04	1183	4148	5078479.00	0.9504
1.0E-02	316	1280	1270618.00	0.7131
1.0E+00	249	712	1249426.00	0.5550
1.0E+02	228	362	1249248.00	0.4430

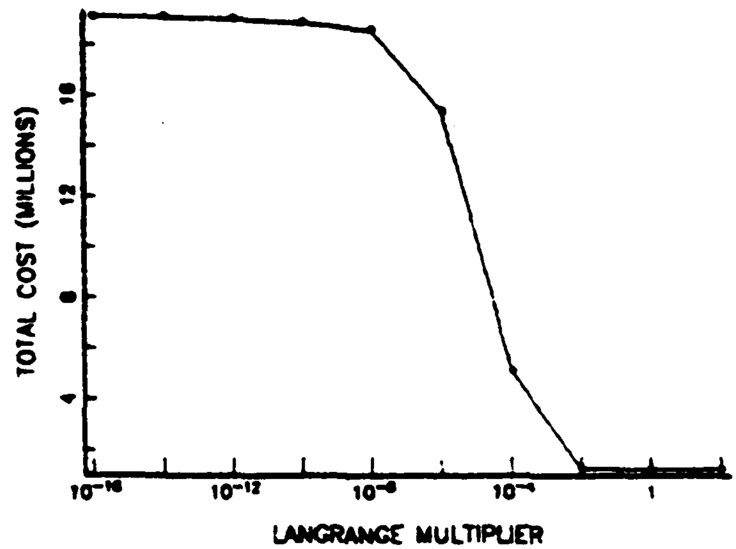


Figure 5. Total Cost Vs. Lagrange Multiplier (Modified RIMAIR, Repairables)

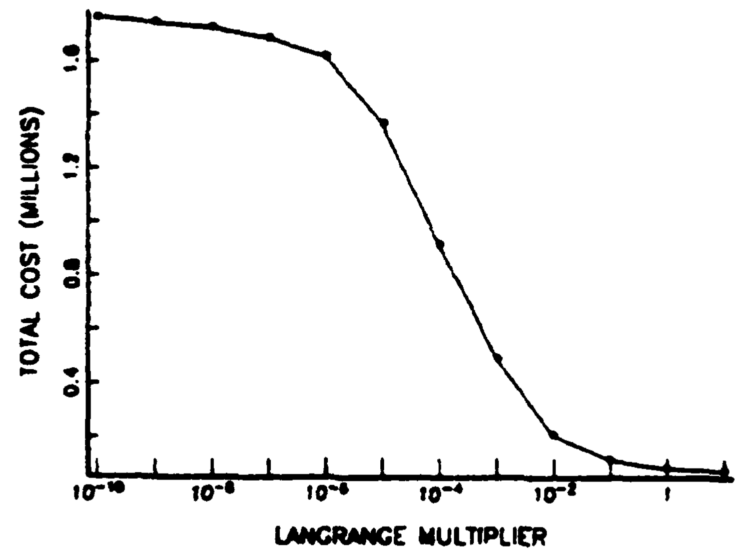


Figure 6. Total Cost Vs. Lagrange Multiplier (Modified RIMAIR, Consumables)

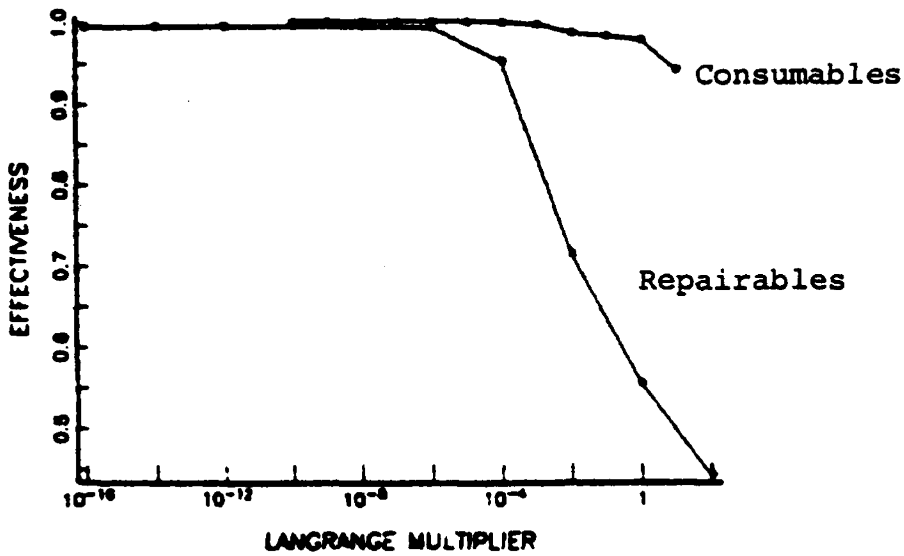


Figure 7. Effectiveness Vs. Lagrange Multiplier
(Modified RIMAIR)

B. SIMULATION RESULTS

The TIGER simulation model was used to test the availability of three different hypothetical systems. Figures 8, 9, and 10 show the reliability block diagrams of the three systems. They were designed to provide increasing redundancy starting with system 1 being a simple series combination. Each system was limited to eight components for demonstration purposes. The components were drawn randomly from the consumable and repairable samples. Table 8 lists the items used with TIGER. Each system was tested with eight consumables and then eight repairables.

Stocking levels were determined based on the following four criteria:

1. Current ASO rules
2. RIMAIR (lambda = 1×10^{-5})
3. RIMAIR with the minimum constraint equal to zero and a total cost equal to the ASO budget
4. Same as (3) with the addition of essentiality codes as discussed in II.B.5.

Table 9 lists the essentiality code for each item under the three systems and Tables 10 and 11 give the stockage levels for each criterion.

Finally, the twelve combinations of systems and stocking levels were run on TIGER for both the consumables and repairables. The average availabilities are shown in Table 12.

From this volume of output comes the following observations. First, is the fact that regardless of the stockage

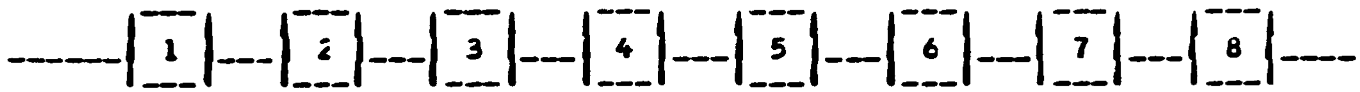
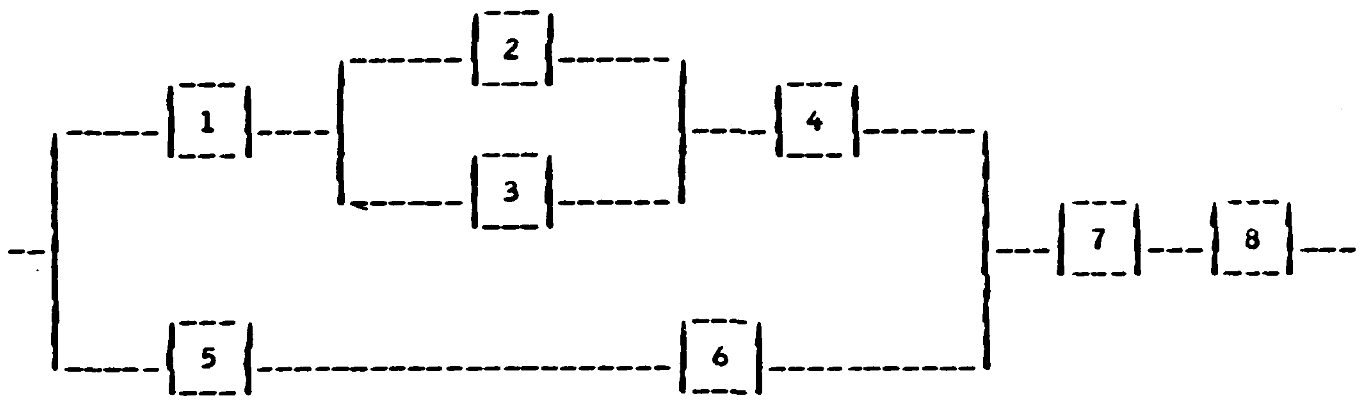


FIGURE 8. BLOCK DIAGRAM OF SYSTEM 1



FIGLRE 9. BLOCK DIAGRAM OF SYSTEM 2

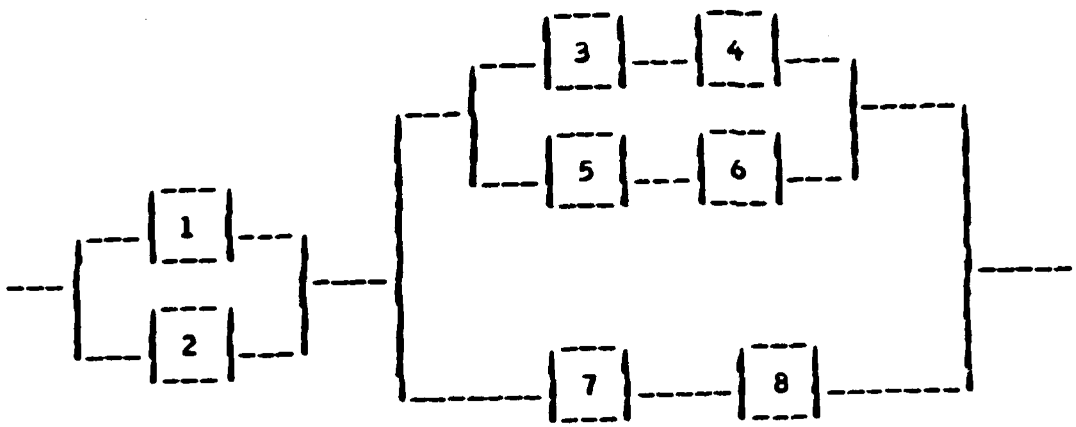


FIGURE 10. BLOCK DIAGRAM OF SYSTEM 3

TABLE 8

ITEMS USED FOR TIGER SIMULATION

ITEM	UNIT PRICE ($)	OSTW (DAYS)	QAP	QAW	MRP	QRW	MTBF (HRS.)
REPAIRABLES							
1	4930.00	62.8	0.0	0.0	0.267	1.849	1168
2	6120.00	62.8	0.0	0.0	0.040	0.713	3029
3	21030.00	62.8	0.0	0.0	0.016	0.211	10237
4	2410.00	62.8	0.0	0.0	0.075	2.244	963
5	456.00	62.8	0.0	0.0	0.007	0.133	10240
6	1250.00	62.8	0.0	0.0	0.0	0.255	8471
7	9840.00	62.9	0.0	0.0	0.073	1.088	1985
8	1500.00	51.9	0.0	0.0	0.0	0.086	25116
CONSUMABLES							
1	0.10	51.9	30.145	43.635	0.0	43.635	50
2	0.15	51.9	0.386	0.751	0.0	0.751	2876
3	0.18	51.9	3.805	6.111	0.0	6.111	353
4	0.29	51.9	1.582	2.237	0.0	2.237	966
5	439.81	51.9	0.0	0.0	0.0	0.0	99999
6	24.82	51.9	6.755	13.136	0.0	13.136	164
7	94.97	51.9	10.443	15.508	0.0	15.508	139
8	55.04	51.9	0.142	0.205	0.0	0.205	10537

TABLE 9

ITEM ESSENTIALITY FOR SYSTEMS 1 THROUGH 3

ITEM	SYSTEM 1	SYSTEM 2	SYSTEM 3
REPAIRABLES			
1	1.5162	.5162	.5162
2	1.2915	.2915	.2915
3	1.1086	.1085	.1086
4	1.5643	.5643	.5643
5	1.0713	.0713	.0713
6	1.1283	.1283	.1283
7	1.3858	1.3858	.3858
8	1.0473	1.0473	.0473
CONSUMABLES			
1	1.9618	.9618	.9618
2	1.3024	.3024	.3024
3	1.7791	.7791	.7791
4	1.5635	.5635	.5635
5	1.0001	.0001	.0001
6	1.8834	.8834	.8834
7	1.8895	1.8895	.8895
8	1.1058	1.1058	.1058

TABLE 10

STOCKAGE LEVELS (REPAIRABLES)

STOCKAGE CRITERION

ITEM	ASO RULES	RIMAIR	MODIFIED RIMAIR	MODIFIED RIMAIR WITH ESSENTIALITY SYST. 1	2	3
1	1	2	0	0	0	0
2	0	1	0	0	0	0
3	0	1	0	0	0	0
4	0	1	1	1	1	1
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	1	0	0	0	0
8	0	0	0	0	0	0
TOTAL COST	4930.	49260.	2410.	2410.	2410.	2410.

TABLE 11

STOCKAGE LEVELS (CONSUMABLES)

STOCKAGE CRITERION

ITEM	ASO RULES	RIMAIR	MODIFIED RIMAIR	MODIFIED RIMAIR WITH ESSENTIALITY SYST. 1	2	3
1	44	676	285	285	282	285
2	1	57	30	30	27	28
3	6	171	81	81	79	80
4	2	85	43	43	40	42
5	0	0	0	0	0	0
6	13	35	19	19	17	19
7	16	33	14	14	14	14
8	0	2	0	0	0	0
TOTAL COST	1248.	4244.	1861.	1861.	1809.	1860.

TABLE 12

AVERAGE AVAILABILITY

STOCKING CRITERION	SYSTEM 1	SYSTEM 2	SYSTEM 3
ASO RULES	.6080/.1921	.8263/.5223	.9906/.9645
RIMAIR	.9540/.7165	.9923/.9240	1.000/.9993
MODIFIED RIMAIR	.7586/.2104	.8044/.5305	1.000/.8156
MODIFIED RIMAIR WITH ESSENTIALITY	.7568/.2104	.8048/.5305	1.000/.8156

level, increases in redundancy increased the availability. While not surprising, it is comforting in terms of credibility. The second observation was also expected. The RIMAIR model provided greater range and total depth at a much higher cost than did the current ASO rules. As a result, the system availability was generally significantly higher. However, the use of redundancy allows the use of lower stockage levels with only minimal loss of system availability. Case in point is System 3 using current ASO rules and RIMAIR stocking levels. While Systems 1 and 2 showed a marked increase in availability using RIMAIR, the redundancy in System 3 made the differences almost negligible (both models gave very high availabilities).

The use of RIMAIR with no minimum constraint shows promising results. In the case of consumables using System

1 there was an increase of 25 percent in availability over that achieved using current ASO rules for essentially the same cost (1848.39 versus 1861.21). With System 2 the current ASO model had a slight edge (.8265 versus .8044), and with System 3 the modified RIMAIR stocking levels had a slight edge (1.000 versus .9906).

In the case of repairables the current rules stocked one unit of Item 1 at a cost of 4930 dollars and the modified RIMAIR model stocked one unit of Item 4 at a cost of 2410 dollars (see Table 10). Systems 1 and 2 showed slightly higher availabilities using the modified RIMAIR rules but the availability for System 3 was significantly higher (.9645 versus .8156) using the current ASO model. The latter case indicates the *importance* of the equipment configuration. With System 1 all the components are in series but with Systems 2 and 3 some components are in parallel (redundancy). For example System 3 will fail if both components 1 and 2 are down. However, because of the arrangement of component 4 in the System 3 configuration, the failure of component 4 will have little impact on system availability. Thus, all other things being equal, a spare for component 1 will provide a greater benefit in terms of System 3 availability than would a spare for component 4. As stated earlier, the modified RIMAIR model selects to stock one unit of component 4 whereas the ASO model stocks one unit of component 1. However, neither model explicitly considers the system configuration in determining stockage levels.

Comparison of the models is made difficult by the problem of trying to force the alternative models to spend nearly equal amounts of money. For consumables the problem was negligible due to the large numbers stocked and the relatively low costs per item. However, for repairables the problem was significant. When trying to compare current ASO stocking levels and modified RIMAIR levels the target cost was $4930.00. The modified RIMAIR model provided two choices. At a lambda (Lagrange multiplier) value of 2×10^{-4} the model stocked one unit of component 4 at a cost of $2410.00. On increasing lambda slightly it would stock one unit of item 4 and one unit of item 1 at a total cost of $7340.00.

The final stocking criterion examined was the modified RIMAIR model with the essentiality codes listed in Table 9. The idea behind the inclusion of an item essentiality code is to attempt to reflect the importance of an item as it pertains to system availability. For example, the essentiality of items 1 and 4 should change sufficiently from System 1 to System 3 so that for System 1, item 4 should be the first stocked, but for System 3, item 1 should be the first item stocked. This would provide for the maximum availability given that only a single part could be stocked (as was the case for the current ASO rules, see Table 10).

Unfortunately, the item essentiality procedure outlined in Section II.B.5 does not provide a large enough difference in the essentiality codes to force such a change. For repairable items, the essentiality codes of Table 9 had no significant effect. For consumable items, the use of the essentiality codes resulted in only minor changes in the stockage levels and no significant differences in system availability.

The ineffectiveness of the proposed essentiality coding scheme would seem to be the result of the lack of discrimination in codes allowed by the scheme. A greater differential is needed to overcome the other factors and to truly reflect such complex relationships imposed by system configuration and redundancy. Such an idea of using essentiality codes is not, however, without merit. The methodology does need additional attention.

V. SUMMARY AND RECOMMENDATIONS

The current ASO rules for AVCAL construction were found inadequate in meeting the CNO's goal for stockage level effectiveness. This led to the development of RIMAIR by FMSO. It was the purpose of this study to investigate RIMAIR as an alternative stocking model for AVCAL's.

The inadequacy of the current rules was confirmed in the case of repairable items. It was also demonstrated that RIMAIR could meet the CNO's effectiveness goals for both repairables and consumables. However, RIMAIR accomplishes this by stocking significantly more items (both range and depth) resulting in much higher cost.

In an effort to compare the two models on an equal cost basis, RIMAIR was modified by deleting the minimum constraint. It was then shown that, for a given budget, the modified RIMAIR model performed significantly better than the current model and was able to satisfy the CNO's effectiveness goal.

The bottom line on any logistics system effort is the ability to keep a weapon system functioning. For this reason the TIGER simulation model was used to evaluate the various stockage criteria outlined in IV.B. in terms of system availability. The RIMAIR stockage levels provided the highest availability, but again at a much higher cost.

The modified RIMAIR model showed some promising results. Under equal cost conditions with total cost set at the current ASO levels, the modified RIMAIR model yielded results which were at least as good as those of the ASO model and, in some cases, significantly better. Finally, an item essentiality scheme was introduced to the modified RIMAIR model. Unfortunately, it demonstrated no significant improvement although it did not detract from the model.

Several areas of this study deserve further investigation. The first is the use of the minimum constraint in the RIMAIR model. It was shown (particularly in the case of consumables) that the constraint forced stockage levels extremely high and severely restricted the flexibility of RIMAIR. The constraints were the driving factor in determining stockage levels, not the optimization model. It was also demonstrated that RIMAIR could function effectively without the minimum constraint. In light of these facts, the justification for and the necessity of the minimum constraint needs to be examined.

Although item essentiality proved ineffective in this study it deserves further investigation. The system used to compute item essentiality was arbitrary with only minimal justification. The development of an item essentiality coding scheme with greater discrimination capability could probably add significantly to system availability results.

APPENDIX A

SAMPLING TECHNIQUE

Due to the large number of data and in an effort to reduce computing time, a stratified random sample was taken. The data were stratified by unit price and quarterly demand with repairable and consumable parts treated as separate populations.

Tables 13 and 14 indicate the stratification scheme along with the corresponding population distributions. Although designed to approximate the Navy's MARK coding system shown in Figure 11, obvious problems necessitated the modification of the strata boundaries. Based on the parent population distributions, a proportional random sampling was drawn (i.e., if ten percent of the parent

TABLE 13

STRATA DISTRIBUTION FOR REPAIRABLES

	UP < 15	15 < UP < 50	50 < UP < 1000	UP > 1000
QRW < .25	.0208	.0233	.0071	.0051
.25 < QRW < 5	.0099	.0094	.0019	.0004
5 < QRW < 20	.1651	.1818	.0171	.0042
QRW > 20	.2242	.2985	.0274	.0038

TABLE 14

STRATA DISTRIBUTION FOR CONSUMABLES

	UP < 15	15 < UP < 50	50 < UP < 1000	UP > 1000
QRW < .25	.2335	.2960	.0732	.0376
.25 < QRW < 5	.0550	.0716	.0081	.0020
5 < QRW < 20	.0817	.1160	.0082	.0020
QRW > 20	.0073	.0075	.0003	.0000

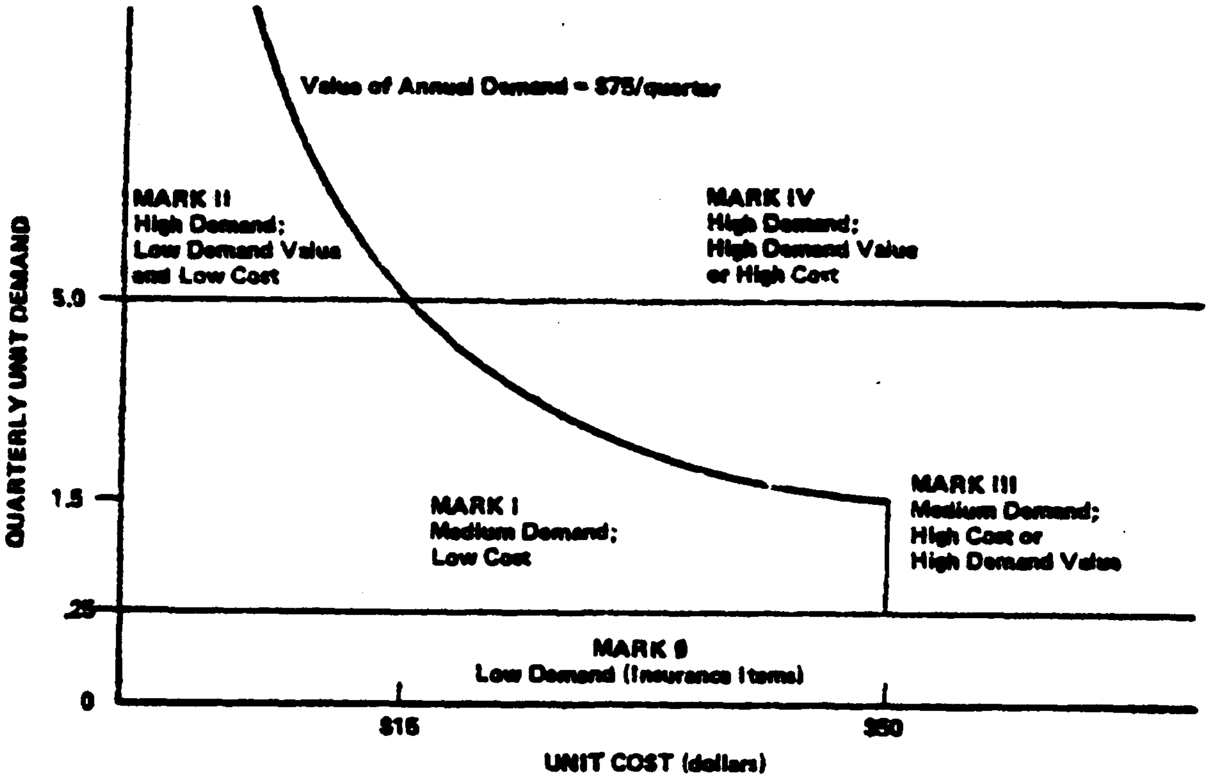


Figure 11. Navy MARK Coding System

population falls in a particular stratum, or cell, then ten percent of the sample was randomly drawn from that cell).

1. Sample Size

Choosing a sample size involves tradeoffs between a sufficiently small sample for computational purposes and an adequately large sample to more accurately reflect the parent population's characteristics. Due to the lengthy computer time required for large data and the number of scenarios (24) used in this study, it was decided to limit the sample size to a maximum of 4000 for each population. Thus, sample size was given priority at the expense of sample accuracy. This tradeoff was acceptable for this comparitive study since all scenarios used the same sample data and thus their relative performance should be unaffected.

In order to measure the sample accuracy, an acceptable coefficient of variation (C.V.) of the sample mean was chosen. By trial and error a C.V. of .1 was found to keep the sample size within the desired 4000 limit. The coefficient of variation is defined as:

$$CV = VAR[\overline{Y}]/\mu \qquad \text{(A-1)}$$

where:

μ = population mean

which leads to,

$$\mathrm{VAR}[\bar{Y}] = (\mathrm{CV}) \times \mu \qquad \text{(A-2)}$$

as the maximum acceptable variation of the sample mean. This is equivalent to saying that for repeated samplings of the parent population, the standard deviation of the sample mean would be no more than CV × 100 percent of the population mean.

Cochran [Ref. 10] provides the following formula for determining sample size (n) for proportional stratified sampling based on the variance of the sample mean ($\mathrm{Var}[\bar{Y}]$):

$$n = n_0(1 + n_0/N) \qquad \text{(A.3)}$$

where:

$$N = \text{parent population size}$$

$$n_0 = \sum w(h)S^2(h)/\mathrm{Var}[\bar{Y}] \qquad \text{(A.4)}$$

$w(h)$ = percent of parent population in cell h (weighting factor)

$S^2(h)$ = variance of the parent population within cell h.

Equations (A.3) and (A.4) indicate the tradeoff discussed earlier between sample size and sample accuracy. As the desired $\mathrm{Var}[\bar{Y}]$ decreases (indicating an increase in sample accuracy) the sample size required to ensure such accuracy increases. The converse is also true.

Implementing Cochran's equation required finding a single value for $\mathrm{Var}[\bar{Y}]$. However, each stratum has a bivariate distribution based on unit price and quarterly demand. This results in three possible values, $Var[\overline{UP}]$, $Var[\overline{QRW}]$ and $Cov[\overline{UP}, \overline{QRW}]$. The covariance term will not always reflect the variability of a population. For example, $Var[\overline{UP}]$ and $Var[\overline{QRW}]$ could be quite large, but if unit price and quarterly demand are independent then $Cov[\overline{UP}, \overline{QRW}] = 0$. For this reason the covariance term was not considered.

The following procedure was followed in choosing between the remaining two terms. Based on a CV of .1 and the population means ($\mu(UP)$, $\mu(QRW)$) the values of $Var[\overline{UP}]$ and $Var[\overline{QRW}]$ were computed. The parent population was stratified based solely on unit price and then solely on demand in order to provide the corresponding strata variances ($S^2(h)$). Utilizing Equations (A.3) and (A.4), a separate sample size was computed for each stratification criterion with the maximum of the two used for this study.

Based on this method, a sample of 1926 repairables from a parent population of 9185 was selected and 3893 consumables from a population of 34,460 were drawn. Tables 15 and 16 compare selected statistics for the samples and parent populations.

It is significant to note that in order to achieve a CV of .1 with a purely random sample a considerably larger sample size would have been required. For example, using the unit prices of the consumable population, an acceptable $Var[\overline{UP}]$ would be:

TABLE 15

REPAIRABLES' SAMPLE VS. POPULATION COMPARISON

	UNIT PRICE STRATIFICATION		QUARTERLY DEMAND STRATIFICATION	
	PARENT POPULATION	SAMPLE	PARENT POPULATION	SAMPLE
MEAN	5642.47	5832.24	1.777	1.720
VARIANCE	$7.98*10^7$	$8.09*10^7$	55.955	33.444
MINIMUM	.01	.01	0.0	0.0
QUANTILES				
.1	97.00	112.00	0.0	0.0
.25	449.00	459.00	.051	.038
.5 (MED.)	1200.00	1180.00	.375	.384
.75	3060.00	2930.00	1.201	1.244
.9	8880.00	9490.00	3.439	3.110
MAXIMUM	10^5	$8.0*10^4$	400.452	91.488

TABLE 16

CONSUMABLES' SAMPLE VS. POPULATION COMPARISON

	UNIT PRICE STRATIFICATION		QUARTERLY DEMAND STRATIFICATION	
	PARENT POPULATION	SAMPLE	PARENT POPULATION	SAMPLE
MEAN	95.551	100.26	3.437	3.419
VARIANCE	517414.0	268979.0	106.708	103.028
MINIMUM	.01	.01	0.0	0.0
QUANTILES				
.1	.180	.17	0.0	0.0
.25	.645	.62	.102	.102
.5 (MED.)	5.00	4.95	.488	.496
.75	39.00	39.00	1.883	1.877
.9	187.81	191.00	7.462	6.960
MAXIMUM	95500.00	17660.00	279.373	110.908

$$\mathrm{Var}[\bar{Y}] = (\mathrm{CV} \times \mu)^2$$

$$= (.1 \times 95.55)^2 = 91.30$$

But for random samples it is know that:

$$\mathrm{Var}[\overline{\mathrm{UP}}] = \mathrm{VAR}[\mathrm{UP}]/n$$

therefore,

$$n = \mathrm{Var}[\mathrm{UP}]/\mathrm{Var}[\overline{\mathrm{UP}}]$$

$$= \frac{517{,}414}{91.30} \approx 5667$$

Thus random sampling would require a sample size of 5667 as opposed to only 3893 for stratified sampling to achieve a CV of .1. Even greater reductions in sample size are achievable if strata boundaries are chosen optimally [Ref. 10].

APPENDIX B

STOCKAGE LEVEL EFFECTIVENESS

A common measure of effectiveness (MOE) for retail inventory models is:

$$\text{STOCKAGE LEVEL EFFECTIVENESS} = \frac{E[\text{DEMANDS SATISFIED}]}{E[\text{DEMANDS}]} \tag{B.1}$$

This MOE is based on the number of demands during a given period of time and the depth of items stocked. The concept of effectiveness is not the same as a fill rate. Fill rate is defined as the probability of satisfying a demand at a particular point in time and is a function of the depth of items stocked and the number of items in the repair/ resupply pipeline at time t. Both concepts are used to calculate the MOE's in Chapter IV.

In the case of consumable parts the calculations are fairly straightforward. Given a stocking level for the ith item (S(i)), there are two possible situations. First, if the demands (X(i)) are less than the stockage levels, then the expected demands satisfied will be X(i). Secondly, if demands exceed stockage levels then the expected demands satisfied will be S(i). Thus,

$$E[\text{DEMANDS SATISFIED}] = \sum_{X(i)=0}^{S(i)} P(X(i))X(i) + \sum_{S(i)+1}^{\infty} S(i)P(X(i))$$

$$= \sum_{0}^{S(i)} P(X(i))X(i) + S(i)(1 - \sum_{0}^{S(i)} P(X(i))) \qquad (B.2)$$

where:

$X(i)$ = demands for item i

$S(i)$ = stocking level for item i

$P(X(i))$ = probability of $X(i)$ demands.

Summing across all items will yield the aggregate demands satisfied.

The expected number of demands is merely the summation across all items of the expected quarterly removals (QRW). Then the stockage level effectiveness can be calculated by simple division.

Repairables present a more complex situation due to the fact that a certain percentage of failures (demands) are repairable and thus can satisfy future demands. Utilizing the repair/resupply pipeline model discussed in Chapter II.A. the following method was employed to compute the stockage level effectiveness.

Given the total attrition at a point in time (A(t)) and the number of units in the repair pipeline (RP), then the fill rate is the conditional probability that at least one unit remained in stock to fill demands. This can be estimated by:

$$FR(S-A(t),t) = \begin{cases} \sum_{R=0}^{S-A(t)-1} P(RP) & \text{if } A(t) < S \\ 0 & \text{if } A(t) \geq S \end{cases} \tag{B.3}$$

where:

S = number of items initially stocked (AVCAL quantity)

P(RP) = probability of having RP items in the repair pipeline

A(t) = total attrition up until time t

FR(S-A(t),t) = fill rate at time t given initial supply of S and attrition of A(t).

But A(t) is not constant given t. Thus by weighting the conditional fill rate by the probability of having A(t) attritions the unconditional expected fill rate at time t is:

$$FR(S,t) = \sum_{A(t)=0}^{S-1} \left[P(A(t)) \times \sum_{R=0}^{S-A(t)-1} P(RP)\right] \tag{B.4}$$

The fill rate above is a continuous non-increasing function of time. However, for computer application a discrete approximation of the expected fill rate was calculated for each day of the endurance period (90 days in this case). Then by multiplying the expected fill rate for each item by its expected daily demand the expected demands satsified was calculated. Summing across all items and all days yielded total expected demands satisfied. As with consumables, the expected demand was merely the summation of quarterly demands for all items and Equation (B.1) was used to compute aggregate effectiveness.

Several significant assumptions and limitations are inherent in the above calculations. In the case of consumables it is assumed that demand is Poisson distributed with mean of QRW. For repairables the following assumptions apply:

1. Demand is stationary over time.
2. The number of items in the repair pipeline is Poisson distributed with mean equal to MRP.
3. The total attrition, A(t), is Poisson distributed with mean equal to $t \times \frac{QAW}{90}$ (t measured in days).
4. Sufficient piece-parts are stocked to repair those failures not BCM.

In light of assumption four, the estimated fill-rate for repairables represents an upper bound on stockage level effectiveness. In reality, as piece-part stocks are depleted the attrition rate will increase (assumption three assumes a constant value). Since piece-part stockage levels are unknown and the fact that not all repairables require piece-parts, the actual effectiveness could not be determined. However, the upper bound calculation suffices for comparison purposes.

APPENDIX C

SAMPLE INPUT AND OUTPUT FOR TIGER SIMULATION MODEL

```
  2    3    0
101    1    1
102    4    1
  5    6    1
103  104    0
  7    8    1
105  106    1
  C    C    0
  8  2.C  50000.00
   493.00
  6120.CO
 21030.00
  2410.00
   456.0C
  1250.00
  9840.CO
  15C0.CO
     2160    9
       1  REPAIRABLE DATA   (LAMBDA = 1E-5)
1000100C 1.01.281234    1
1.     2160.

       1
       0
    1.C        0.0 1.0 1.0
       1          002327679   1168.2 1.0 1.0312.
       2          001165478   3029.5 1.0 1.0121.
       3          001646843  10237.0 1.0 1.0164.
       4          002876362    962.6 1.0 1.0 72.
       5          002252424  16240.6 1.0 1.0114.
       6          002875511   8470.6 1.0 1.0   0.
       7          000408864   1985.3 1.0 1.0145.
       8          010072171  25116.3 1.0 1.0   0.

       1    1
       2    2
       3    3
       4    4
       5    5
       6    6
       7    7
       8    8

                                       1.0
       2  10C    0
       1  100    0
       1  10C    0
       1  10C    0
       0    C    0
       0    C    0
       1  10C    0
       0    0    0
    SYST    1    2  999       0.0
     SS1    1       503       0.0
     SS2    1       505       0.0
       1  501    2    3
       2  502    5    6
       2  503    7    8
       3  504    1    4  501
       1  505  504  502
       2  999  505  503

SPRSAPPL
```

```
JCC=          1
                               REPAIRABLE DATA  (LAMBDA = 1E-5)

 ++++++++++++++++++   TIGER  ++++++++++++++++++

++ NAVSEC 6112 LUETJEN+MANDEL+VAIL+ALLEY+BROWN ++

++NPS IBM/360 VERSION LT. J. LEATHER THESES 9/80++

++AS AMENDED BY LCDR. P.J. O'REILLY THESES 12/81++

RANDCM SEED IS 1234
  1000  1000  1.00   1.28    1234    1
        PHASE SEQUENCE  TYPE  DURATION  CUM TIME
                   1      1   2160.00   2160.00
       1       0   0   0   0   0   0   0   0   0   0   0   0   0
  0
     1.00     0.0      1.00     1.00

TYPE  NAME                  MTBF      MTTR       DC        ADT1     ADT2
   1         002327679     1168.2      1.00     1.000     312.0     0.0
   2         001165478     3029.5      1.00     1.000     121.0     0.0
   3         001646843    10237.0      1.00     1.000     164.0     0.0
   4         002876362      962.6      1.00     1.000      72.0     0.0
   5         002252424    16240.6      1.00     1.000     114.0     0.0
   6         002875511     8470.6      1.00     1.000       0.0     0.0
   7         000408864     1985.3      1.00     1.000     145.0     0.0
   8         010072171    25116.3      1.00     1.000       0.0     0.0

TYPE  EQUIPMENT
   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   2   2   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   3   3   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   4   4   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   5   5   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   6   6   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   7   7   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   8   8   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
       1          2      100       0             1.00
       2          1      100       0             1.00
       3          1      100       0             1.00
       4          1      100       0             1.00
       5          0        0       0             1.00
       6          0        0       0             1.00
       7          1      100       0             1.00
```

```
        8             0           0          0                 1.00
  THE MISSION WILL BE RUN WITH   1 PHASE TYPES IN VARIABLE SEQUENCE.
SYST   1   2 995      0.0
 SS1   1   0 503      0.0
 SS2   1   0 505      0.0
  1 501   2   3   0   0   0   0   0
  2 502   5   6   0   0   0   0   0
  2 503   7   8   0   0   0   0   0
  3 504   1   4 501   0   0   0   0
  1 505 504 502   0   0   0   0   0
  2 999 505 503   0   0   0   0   0
ANOTHER SET OF 50MISSIONS WILL BE RUN TO OBTAIN REQUIRED STATISTICAL CONFIDENCE
ANOTHER SET OF 50MISSIONS WILL BE RUN TO OBTAIN REQUIRED STATISTICAL CONFIDENCE
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ANOTHER SET OF 50MISSIONS WILL BE RUN TO OBTAIN REQUIRED STATISTICAL CONFIDENCE

A GRAND TOTAL OF  1000 MISSIONS HAVE BEEN RUN.
THE RELIABILITY IS          0.2310
THE LOWER CONF LIMIT IS     0.2139
THE SPEC REQUIREMENT IS     1.0000
THE READINESS IS            0.5359
THE AVERAGE AVAILABILITY IS    0.9240
THE INSTANT AVAILABILITY IS    0.8440

THE MEAN TIME BETWEEN MISSION FAILURES IS               1505.6
THE LCL,90, MTBMF IS                   440.8
THE MTBMF VARIANCE IS                     692080.6

THE SYSTEM MUT IS              1200.2
THE SYSTEM MDT IS              49.972
SIMULATION COMPLETE-OPTIMUM NUMBER MISSIONS WERE RUN
    EQUIP FAILURES AND CORRECTIVE MAINTENANCE(CM) SUMMARY
```

EQUIP. NC.	TYPE NO.	TOTAL EQUIP. FAILURES	AVG. NO. FAILURES PER MISSION	AVG. CM MANHOURS PER MISSION
1	1	1710	1.710	1.710
2	2	724	0.724	0.724
3	3	218	0.218	0.218
4	4	2107	2.107	2.107
5	5	137	0.137	0.137
6	6	230	0.230	0.230
7	7	1055	1.055	1.055
8	8	79	0.C79	0.079
		6260	6.260	6.260

AVERAGE NUMBER OF SPARES USED PER MISSION

SPARES TYPE	SHIP STOCK	USED	TENDER STOCK	USED	BASE STOCK	USED
1	2	1.38	100	0.33	0	0.0
2	1	0.51	100	0.22	0	0.0
3	1	0.20	100	0.02	0	0.0
4	1	0.89	100	1.22	0	0.0
7	1	0.68	100	0.38	0	0.0

REPAIRABLE CATA (LAMBDA = 1E-5)

CRITICAL EQUIPMENTS

UNAVAILABILITY AND
PERCENT OF UNAVAILABILITY

NAME	NUM HRS	UNAVA	PERCENT
010072171	78902.0000	0.0365	48.09
000408864	51029.0352	0.0236	31.10
002875511	10336.3516	0.0048	6.30
002876362	8473.7070	0.0039	5.16
002327679	8117.6992	0.0038	4.95
002252424	7046.7891	0.0033	4.29
001165478	0.0674	0.0000	0.00
001646843	0.0674	0.0000	0.00

REPAIRABLE DATA (LAMBDA = 1E-5)

CRITICAL EQUIPMENTS

UNRELIABILITY AND
PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	EQUIP NO.
000408864	592.0	0.5920	76.98	7	7
010072171	40.0	0.0400	5.20	8	8
C02875511	38.7	0.0387	5.03	6	6
002876362	36.5	0.0365	4.75	4	4
C02327679	31.2	0.0312	4.05	1	1
002252424	30.7	0.0307	3.99	5	5

TOTAL NO. MISSIONS=1000
TOTAL NO. MISSICN FAILURES= 769

APPENDIX D

RIMAIR AND ASO PROGRAMS

```
C       BROOKS O. BCATWRIGHT
C       THESIS
C
C       THIS PROGRAM INCORPORATES THE CURRENT ASO RULES FOR AVCAL SPARES
C       INVENTORY LEVELS.
C
C
        INTEGER NIIN(3), NRANGE, NDEPTH, TOTDEP, AVCAL
        INTEGER NITEMS
        REAL UP,CR,OSTW,QAP,QAW,MRP,QRW,TCOST,COST,FR,TFILLS,TOTDEM
        REAL MULT(4)
C       INITIALIZE VARIABLES
        MULT(1)=1.0
        MULT(2)=1.1
        MULT(3)=1.5
        MULT(4)=2.0
        WRITE (6,200)
        DO 90 K=1,4
        DATA R/'R'/
        NDEPTH = 0
        TOTDEP = 0
        NRANGE = 0
        TCOST = 0.0
        COST = 0.0
        NITEMS = 0
        TFILLS = 0.0
        TOTDEM = 0.0
        REWIND 2
5       READ (2,500,END=30) (NIIN(I),I=1,3),UP,CR,OSTW,QAP,QAW,MRP,QRW
        QRW=MULT(K)*QRW
        MRP=MULT(K)*MRP
        QAW=MULT(K)*QAW
        NITEMS = NITEMS +1
        IF (CR .EQ. R) GO TO 10
           CALL CONMOD(UP,QAW,AVCAL)
           GO TO 20
10      CONTINUE
           CALL REFMOD(UP,QAW,MRP,AVCAL)
20      CONTINUE
        IF (AVCAL .EQ. 0) GO TO 25
           TCOST = TCOST + (UP*AVCAL)
           NDEPTH = NDEPTH + AVCAL
           NRANGE = NRANGE + 1
           CALL FILRAT (MRP,QAW,QRW,CR,AVCAL,EFILLS)
           TOTDEM = TOTDEM + QRW
           TFILLS = TFILLS + EFILLS
25      CONTINUE
C       WRITE(6,510) (NIIN(I),I=1,3),UP,CR,OSTW,QAP,QAW,MRP,QRW,AVCAL
```

```
      GO TO 5
30    CONTINUE
      RATIO = FLOAT(NRANGE)/FLOAT(NITEMS)
      FR = TFILLS/TOTDEM
      WRITE (6,300) NRANGE,RATIO,NDEPTH,TCOST,FR
90    CCNTINUE
      STOP
100   FORMAT (/,3A3,5X,I5,5X,F9.2,5X,F8.3,5X,F8.3)
200   FORMAT ('RANGE',4X,'RANGE PERCENTAGE',4X,'DEPTH',4X,'TOTAL COST'
     *,4X,'EFFECTIVENESS')
300   FORMAT(I5,10X,F5.3,7X,I6,F15.2,3X,F10.4)
500   FORMAT (3A3,1X,F9.2,1X,A1,1X,F4.1,1X,F8.3,1X,F8.3,1X,F8.3,1X,F9.3)
510   FORMAT (3A3,1X,F9.2,1X,A1,1X,F4.1,1X,F8.3,1X,F8.3,1X,F8.3,1X,F9.3,
     *1X,I4)
      END
C
C
      SUBROUTINE REPMOD (UP,QAW,MRP,AVCAL)
      INTEGER AVCAL,I,RP,AA
      REAL UP,QAW,MRP,CDFL,CDFH,PROBI
      AVCAL = 0
      RP = 0
      AA = 0
      I = 0
      IF (MRP .LT. .11) GO TO 40
         IF (MRP .LT. 20.0) GO TO 10
               RP = 1.28166667*(MRP**.5)+MRP+.5
               GO TO 40
10       CONTINUE
               PROBI = EXP(-MRP)
               CDFH = PROBI
15             IF (CDFH .GE. .90) GO TO 20
                   I = I + 1
                   PROBI = PROBI*MRP/FLOAT(I)
                   CDFL = CDFH
                   CDFH =CDFH + PROBI
                   GO TO 15
20             CONTINUE
               IF (ABS(CDFH - .9) .GE. ABS(CDFL - .9)) GO TO 30
                   RP = I
                   GO TO 40
30             CONTINUE
                   RP = I - 1
40    CONTINUE
      IF (RP .EQ. 0) GO TO 70
         IF (QAW .LT. 1.0)GO TO 50
               AA = MAX(1,INT(QAW+.5))
               GO TO 60
```

```
50       CONTINUE
             AA = 0
60       CONTINUE
         AVCAL = RP + AA
         GO TO 80
70    CCNTINUE
      CALL CONMOD(UP,QAW,AVCAL)
80    CONTINUE
      RETURN
      END
C
C
      SUBROUTINE CONMOD(UP,QAW,AVCAL)
      INTEGER AVCAL
      REAL UP,QAW
      AVCAL = 0
      IF (UP .LT. 5000.0) GO TO 10
         IF (QAW .GE. .5) AVCAL = MAX (1,INT(QAW+.5))
         GO TO 20
10    CCNTINUE
         IF (QAW .GE. .34) AVCAL = MAX (1, INT(QAW + .5))
20    CONTINUE
      RETURN
      END
C
      SUBROUTINE FILRAT (MRP,QAW,QRW,CR,OPTMAL,EFILLS)
      INTEGER OPTMAL,I,AI,RP,SMAI
      REAL QRW,PS,SUM,SUM1,EFILLS
      REAL MRP,QAW,FRI,MAI,PAI,CUMRP,PROBRP
      DATA C/'C'/
C
      IF (OPTMAL .GT. 0) GC TO 5
         EFILLS = 0.0
         GO TO 90
5     CONTINUE
      IF (CR .NE. C) GO TO 20
         PS = EXP(-QRW)
         SUM = PS
         SUM1 = 0.0
         DO 10 I=1,OPTMAL
            PS = PS*QRW/FLOAT(I)
            SUM = SUM + PS
            SUM1 = SUM1 + (PS*FLOAT(I))
10       CONTINUE
         EFILLS = (OPTMAL*(1-SUM))+SUM1
         GO TO 90
20    CONTINUE
      EFILLS = 0.0
```

```
      DO 50 I =1,90
         FRI = 0.0
         MAI = FLCAT(I)*QAW/90.0
         PAI = EXP(-MAI)
         DO 40 AI = 1,OPTMAL
            PROBRP = EXP(-MRP)
            CUMRP = PROBRP
            SMAI = OPTMAL - AI
            IF (SMAI .EQ. 0) GO TO 30
            DO 30 RP = 1,SMAI
               PROBRP = PROBRP*MRP/FLOAT(RP)
               IF (PROBRP .LT. 1E-64) PROBRP = 0.0
               CUMRP = CUMRP + PROBRP
30          CONTINUE
            DUM = PAI*CUMRP
            IF (DUM .LT. 1E-64)DUM = 0.0
            FRI = FRI +DUM
            PAI = PAI*MAI/FLOAT(AI)
            IF (PAI .LT. 1E-64)PAI = 0.0
40       CONTINUE
         EFILLS = EFILLS + (FRI*QRW/90.0)
50    CCNTINUE
90    CONTINUE
      RETURN
      END
```

```
C****************************************************************** 00010300
C-->MAIN PORTION OF RIMAIR MODEL                                    00010310
C                                                                   00010320
      INTEGER OPTMAL,NIIN(3),NR,NDEPTH,I,J,K                        00010340
      REAL L, ESS,TCOST,WP,GR,OLP,COST,END,EFILLS,OLW               00010350
      REAL RDT,UP,QAW,QAP,QRW,MRP,OSTW,OSTP,FR,TFILLS,TOTDEM
      DATA C/'C'/
      L = 4.00E-4
      WRITE(6,900)                                                  00010940
C     INITIALIZE VARIABLES
      NR=0                                                          00010360
      NDEPTH=0                                                      00010370
      TCOST=0.0                                                     00010380
      ESS=1.0                                                       00010390
      RDT= 0.0                                                      00010410
      TFILLS = 0.0
      TOTDEM = 0.0
      REWIND 2
5     READ(2,850,END=50) (NIIN(I),I=1,3),UP,CR,OSTW,QAP,QAW,MRP,QRW,ESS 00010440
C     ESS=1.0                                                       00010390
      OSTP=OSTW                                                     00010448
C-->CALCULATE WARTIME PIPELINE                                      00010460
      WP=MRP+(OSTW+RDT)*QAW/90.0                                    00010480
      IF(WP.EQ. 0.0)  GO TO 5                                       00010485
C-->BEGIN THE EVALUATION                                            00010500
      CALL COMPOL (UP,QAP,QAW,OLP,OLW)                              00010520
C-->CCNSUMABLE CCNPONENT?  IF SO, COMPUTE WARTIME PIPELINE          00010540
      IF(OLP.LE.1)  GO TO 19                                        00010551
      IF(CR.EQ. C )  WP=WP+(OLP-1.0)/2.0                            00010560
19    CCNTINUE                                                      00010592
C-->CALCULATE ENDURANCE QUANTITY                                    00010580
      END=QAW*(1-(RDT/90.0)-(OSTW/90.0))+(QAP*OSTP/90.0)            00010600
C-->END MUST BE ZERO OR GREATER                                     00010620
      IF(END.LT.0.0)  END=0.0                                       00010640
C-->CALCULATE BASIC PIPELINE                                        00010660
      GR=WP+END                                                     00010680
C-->CALL APPROPRIATE SUBROUTINE BASED ON WARTIME PIPELINE           00010700
      IF(WP.GE.5)  GO TO 10                                         00010720
         CALL POISON (WP,GR,L,UP,QRW,ESS,OPTMAL,OLP)                00010740
      GO TO 20                                                      00010750
10    CALL NORMAP (OLP,L,WP,UP,QRW,ESS,GR,OPTMAL)                   00010770
20    CALL AVCAL (GR,OLP,OPTMAL,UP,COST)                            00010810
      TCOST=TCOST+COST                                              00010850
      IF(OPTMAL.EQ.0)  GO TO 5                                      00010870
         CALL FILRAT (MRP,QAW,QRW,CR,OPTMAL,EFILLS)
         TFILLS = TFILLS + EFILLS
         TOTDEM = TOTDEM + QRW
         NR=NR+1                                                    00010890
```

```
      NDEPTH=NDEPTH+OPTMAL
      GO TO 5
50    CONTINUE
      FR = TFILLS/TOTDEM
      WRITE(6,910) L,NR,NDEPTH,TCOST,FR
C0    CONTINUE
      STOP
800   FORMAT (E8.3,1X,3A3,1X,F9.2,1X,A1,1X,F4.1,1X,F8.3,1X,F8.3,1X,F8.3,
     *1X,F9.3,1X,I5)
850   FORMAT (3A3,1X,F9.2,1X,A1,1X,F4.1,1X,F8.3,1X,F8.3,1X,F8.3,1X,F9.3,
     *1X,F7.4)
860   FCRMAT (3A3,1X,F9.2,1X,A1,1X,F4.1,1X,F8.3,1X,F8.3,1X,F8.3,1X,F9.3,
     *1X,I4,1X,F7.4)
900   FORMAT (5X,'LAMBDA VALUE',6X,' RANGE ',7X,' DEPTH ',5X,'TOTAL COST
     *',5X,'EFFECTIVENESS',//)
910   FORMAT (3X,E12.4 ,9X,I4,7X,I7,5X,F14.2,F10.4)
      END
C
      SUBROUTINE COMPOL (UP,QAP,QAW,OLP,OLW)
C
      REAL UP,QAP,QAW,OLP,OLW
      OLP=((558.6086957*QAP)/UP)**0.5
      OLW=((558.6C86957*QAW)/UP)**0.5
      RETURN
      END
C*****************************************************************
      SUBROUTINE POISON (WP,GR,L,UP,QRW,ESS,OPTMAL,CLP)
      INTEGER S, CPTMAL,MAX
      REAL L, MN, ESS, WP, GR, UP, QRW, A, PS3, CT, PS
      REAL OLP,WP
      MN = 0.0
      A=0.99
      MAX=0
      PS3=EXP(-GR)
      CT=PS3
5     IF(CT.GE.A)  GO TO 7
         MAX=MAX+1
         PS3=PS3*GR/FLOAT(MAX)
         CT=CT+PS3
         GO TO 5
7     CCNTINUE
      MAX=MAX+OLP-1+0.5
C-->TRUNCATE WARTIME PIPELINE TO INTEGER VALUE
      S=WP
C-->CALCULATE POISSON DISTRIBUTION OF MEAN WARTIME PIPELINE
      PS=EXP(-WP)
C-->CALCULATE POISSON DISTRIBUTION OF BASIC PIPELINE
      PS2=EXP(-GR)
```

```
C-->ASSIGN CS POISSON OF GR                                             00011940
      CS=PS2                                                            00011960
C-->CALCUALTE MINIMUM STOCK                                             00011980
      IF (QRW .NE. 0.0) MN=(L*UP)/(QRW*ESS)                             00012000
C-->OPTIMIZATION LOOP                                                   00012020
      IF(S.EQ.0)  GO TO 15                                              00012035
      DO 10  I=1,S                                                      00012040
         PS=(PS*WP)/FLOAT(I)                                            00012080
         PS2=(PS2*GR)/FLOAT(I)                                          00012090
10    CS=CS+PS2                                                         00012100
C-->COMPARE WARTIME PIPELINE POISSON VALUE WITH                         00012120
C   MINIMUM STOCK, IF LOWER, BRANCH                                     00012130
15    IF(PS.LT.MN)  GO TO 40                                            00012150
20       IF(CS.GE.A)  GO TO 30                                          00012190
            IF(PS.LT.MN)  GO TO 40                                      00012230
            S=S+1                                                       00012270
C-->CALCULATE NEW POISSON VALUES AND CS                                 00012290
            PS=(PS*WP )/FLOAT(S)                                        00012310
            PS2=(PS2*GR)/FLOAT(S)                                       00012320
            CS=CS+PS2                                                   00012330
            GO TO 20                                                    00012350
30       IF(PS.LT.MN)  GO TO 40                                         00012370
            IF(S.GE.MAX)  GO TO 40                                      00012375
            S=S+1                                                       00012380
            PS=PS*WP/FLOAT(S)                                           00012385
            GO TO 30                                                    00012390
40    CONTINUE                                                          00012430
      OPTMAL= S                                                         00012440
      RETURN                                                            00012450
      END                                                               00012460
C*********************************************************************   00012470
C-->NORMAL APPROXIMATION TO POISSON                                     00012490
C
      SUBROUTINE NORMAP (OLP,L,WP,UP,QRW,ESS,GR,CPTMAL)                 00012620
      INTEGER OPTMAL,LMN,NNP                                            00012640
      REAL ESS,PI,OLP,OLW,L,WP,UP,QRW,GR                                00012650
      PI=3.1415926535                                                   00012660
C-->CALCULATE APPROXIMATION OF MINIMUM STOCK USING NORMAL APP           00012680
      AMN=(L*UP*(2*PI*WP)**0.5)/(QRW*ESS)                               00012700
C-->COMPARE APPROXIMATION TO ONE, BRANCH IF LESS OR EQUAL               00012720
      IF(AMN.LE.1)  GO TO 10                                            00012740
C-->SET OPTMAL EQUAL TO ZERO, RETURN TO MAIN                            00012760
         OPTMAL=0                                                       00012780
         RETURN                                                         00012790
C--> CALCULATE LMN AND NNP (ROUNDUP)                                    00012810
10    LMN=WP+1+((-2)*WP*ALOG(AMN))**0.5                                 00012830
      NNP=2.33*(GR**0.5)+GR+OLP                                         00012850
      IF(NNP.LT.LMN)  GO TO 20                                          00012890
```

```
C-->SET OPTMAL EQUAL TO LMN, RETURN TO MAIN
         OPTMAL=LMN
         RETURN
C-->SET OPTMAL EQUAL TO NNP, RETURN TO MAIN
20    OPTMAL=NNP
      RETURN
      END
C*******************************************************************
C-->COMPUTE AVCAL
C
      SUBROUTINE AVCAL (GR,OLP,OPTMAL,UP,COST)
      INTEGER OPTMAL,MIN,IAVCAL
      REAL A,GR,CLP,OLW,UP,COST
      A=0.5
C-->COMPARE GROSS REMOVALS TO CONSTANT, IF LOW, BRANCH
      IF(GR.LT.A)  GO TO 10
C-->COMPARE OPERATING LEVEL TO ONE, SET EQUAL TO ONE IF LOW
         IF(OLP.LT.1)   OLP=1
10    MIN=OLP+GR+0.5
C-->COMPARE OPTMAL TO MIN, BRANCH IF EQUAL OR GREATER
      IF(OPTMAL.GE.MIN)   GO TO 20
C-->SET IAVCAL EQUAL TO MIN
         IAVCAL=MIN
         GO TO 30
C-->SET IAVCAL EQUAL TO OPTMAL
20    IAVCAL=OPTMAL
C-->CALCULATE COST AND RETURN TO MAIN
30    COST=FLOAT(IAVCAL)*UP
      OPTMAL=IAVCAL
      RETURN
      END
C*******************************************************************
C-->COMPUTE EXPECTED FILLS
C
C*******************************************************************
C-->COMPUTE EXPECTED FILLS
C
      SUBROUTINE FILRAT (MRP,QAW,QRW,CR,OPTMAL,EFILLS)
      INTEGER OPTMAL,I,AI,RP,OPTM1
      REAL QRW,PS,SUM,SUM1,EFILLS
      REAL MRP,QAW,FRI,MAI,PAI,CUMRP(1000),PROBRP
      DATA C/'C'/
C
      IF (OPTMAL .GT. 0) GO TO 5
         EFILLS = 0.0
         GO TO 90
5     CONTINUE
      IF (CR .NE. C) GO TO 20
```

```
      PS = EXP(-QRW)
      SUM = PS
      SUM1 = 0.0
      DO 10 I=1,OPTMAL
         PS = PS*QRW/FLOAT(I)
         IF (PS .LT. 1E-64) PS = 0.0
         SUM = SUM + PS
         SUM1 = SUM1 + (PS*FLOAT(I))
10    CONTINUE
      EFILLS = (OPTMAL*(1-SUM))+SUM1
      GO TO 90
20    CONTINUE
      EFILLS = 0.0
      PROBRP = EXP(-MRP)
      CUMRP(1) = PROBRP
      OPTM1 = OPTMAL -1
      IF (OPTM1 .EQ. 0) GO TO 30
      DO 30 RP = 1,OPTM1
         PROBRP = PROBRP*MRP/FLOAT(RP)
         IF (PROBRP .LT. 1E-64) PROBRP = 0.0
         CUMRP(RP+1) = CUMRP(RP) + PROBRP
30    CONTINUE
      DO 50 I =1,90
         FRI = 0.0
         MAI = FLOAT(I)*QAW/90.0
         PAI = EXP(-MAI)
         DO 40 AI = 1,OPTMAL
            DUM = PAI*CUMRP(OPTMAL-AI+1)
            IF (DUM .LT. 1E-64)DUM = 0.0
            FRI = FRI +DUM
            PAI = PAI*MAI/FLOAT(AI)
            IF (PAI .LT. 1E-64)PAI = 0.0
40       CONTINUE
         EFILLS = EFILLS + (FRI*QRW/90.0)
C     WRITE(6,*) EFILLS
50    CONTINUE
90    CONTINUE
      RETURN
      END
```

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